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Article

Características dinámicas de 22 maderas determinadas por el método de vibraciones transversales

Dynamic characteristics of 22 woods determined by the tranverse vibration method

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Resumen

La industria de la madera requiere información sobre las características tecnológicas del material para que se les incorpore a nuevos productos con valor agregado. El objetivo de la investigación que se describe fue determinar la densidad, el módulo dinámico, el módulo de rigidez y el coeficiente de amortiguamiento de 22 especies. De cada una se prepararon 20 probetas y se realizaron pruebas de vibraciones en condiciones de apoyo libre-libre. Se calcularon el módulo de dinámico, el módulo de rigidez y el coeficiente de amortiguamiento. Para cada variable se calculó la media, desviación estándar y coeficiente de variación. La especie se consideró el factor de variación. Se obtuvieron las regresiones lineales para un nivel de significancia de 95 % y los coeficientes de determinación de las variables en función de la densidad. Cada taxon presentó características dinámicas diferentes, lo que permitió observar el amplio intervalo de valores que se pueden presentar entre diferentes taxa. La densidad se distribuyó en un intervalo amplio con un mínimo de 391 kg m^{-3} (*Gyrocarpus americanus*) y un máximo de 1 096 kg m^{-3} (*Tabebuia chrysantha*). Y se mostró como un buen predictor tanto del módulo dinámico (R^2 = 0.86), como del módulo de rigidez (R^2 = 0.79). No se registró una correlación significativa del coeficiente de amortiguamiento con la densidad (R^2 = 0.01).

Palabras clave: Características tecnológicas, coeficiente de amortiguamiento, densidad de la madera, módulo de rigidez, módulo dinámico, probetas.

Abstract

The timber industry requires information on the technological characteristics of the material so that they are incorporated in new products with added value. The aim of the research was to determine the density, dynamic modulus, modulus of rigidity and damping ratio of 22 species. For each species, 20 specimens were prepared and vibration tests were conducted under free-free condition support. Dynamic modulus, modulus of rigidity and the damping coefficient were assessed. For each variable the mean, standard deviation and coefficient of variation were calculated. Linear regressions were calculated for a significance level of 95 % and their coefficients of determination of the variables as a function of density. Each species showed different dynamic characteristics, which allowed to observe the wide range of values that can be found between different species. The density values are distributed among a minimum of 391 kg m^{-3} (*Gyrocarpus americanus*) and a maximum of 1 096 kg m^{-3} (*Tabebuia chrysantha*), which allowed to examine a wide interval of densities. The density was found to be a good predictor of dynamic modulus (R^2 = 0.86) and modulus of rigidity (R^2 = 0.79). No significant correlation of damping ratio with density was found (R^2 = 0.01).

Key words*:* Technological characteristics, damping coefficient, wood density, modulus of rigidity, dynamic modulus, specimens.

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Introduction

The forest products industry requires updated information on the technological characteristics of wood to be incorporated into new products with added value. The absence of physical and mechanical parameters of species with potential for industrial uses has the consequence that wood is not appreciated as a standardized material to be integrated rationally in the manufacture of new products and in wood construction. A contribution to the solution of this problem is to determine experimentally its useful characteristics for engineering calculation and design (Labonnote *et al.,* 2015).

The dynamic module and the rigidity module are characteristics that refers to the ability of a material to store elastic energy when deformed. When a structural element of wood is subjected to a deformation in bending, both parameters are related to the deformations corresponding to the combined bending and shear stresses. Hence, the dynamic module and the rigidity module have application in the probabilistic calculation of structures (Köhler *et al.,* 2007) and in their numerical modeling (Sucharda *et al.,* 2015).

The damping coefficient is a material property that represents the internal friction caused by dynamic stresses. This parameter is used as a reference in the characterization of species with vocation for the elaboration of articles whose function is the control of noise, the reduction of vibrations and the prevention of fatigue in structural elements (Ouis, 2003).

Vibrations are a non-destructive evaluation method to determine the mechanical characteristics of wood (Pellerin and Ross, 2002). In particular, transverse vibrations are used to determine the dynamic modulus (Hamdam *et al.,* 2009), the rigidity modulus (Da Silva et al., 2012) and the damping coefficient (Brémaud *et al.,* 2010). In the same way, this technique is effective to describe wood composite products (Jae-Woo *et al.,* 2009; Wang *et al.,* 2012), to determine the elastic properties used in wood structures (Piter *et al.,* 2004; Olsson *et al*., 2012) and as a non-destructive method to make predictions of structural wood resistance (Ross, 2015).

There are few precedents about the mechanical characterization of the 22 woods under study. Tamarit and López (2007) and Silva *et al.* (2010) describe some of the technological characteristics of various forest species. For four, the review of the country's bibliography shows little information regarding its dynamic properties (Sotomayor, 2015). Therefore, the objective of this research was to determine the density, the dynamic modulus, the rigidity modulus and the damping coefficient of 22 Mexican wood species.

Materials and Methods

Materials

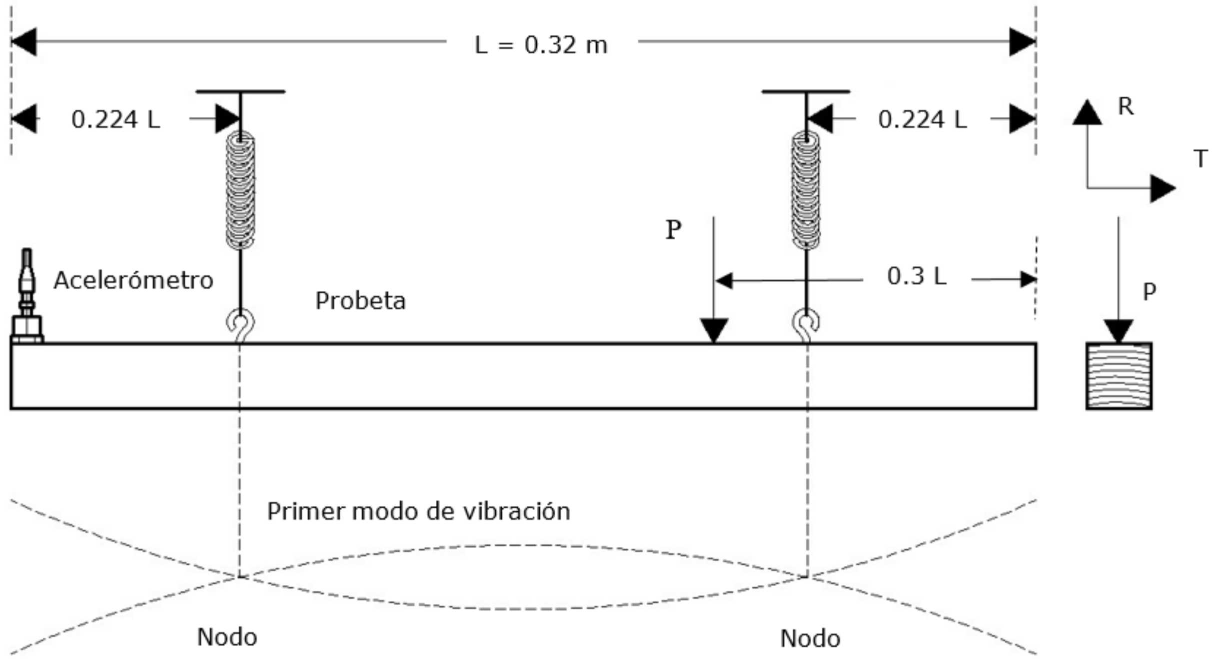
The experimental material consisted of pieces of sawn wood of 22 native forest species, from natural growth forests, collected in sawmills of Mexico. The pieces of wood were cut from the first log of the commercial trunk of different trees. The species were identified in the *Laboratorio de Mecánica de la Madera*, de la *Facultad de Ingeniería en Tecnología de la Madera*, of the *Universidad Michoacana de San Nicolás de Hidalgo* (Laboratory of Wood Mechanics, of the Faculty of Engineering in Wood Technology, of the *Michoacán* University of *San Nicolás de Hidalgo*). Table 1 lists the species under study.

Table 1. Dynamic characteristics of 22 woods.

	Sspecies		ρ (kg m^{-3})	E_{vt} (MN m^{-2})	G_{vt} (MN m^{-2})	ζ_{vt} -
1	*Gyrocarpus americanus* Jacq.	$\bar{X}$	391	6 276	548	0.023
		CV	3.5	18.7	34.6	43.5
2	*Tilia mexicana* Schltdl.	$\bar{X}$	442	10 133	491	0.018
		CV	12.6	10.6	37.4	50.0
3	*Enterolobium cyclocarpum* (Jacq.) Griseb	$\bar{X}$	448	6 076	582	0.035
		CV	7.9	39.9	37.6	57.1
4	*Cupressus lindleyi* Klotzsch ex Endl.	$\bar{X}$	486	9 058	1 031	0.025
		CV	13.4	35.4	41.5	72.0
5	*Cedrela odorata* L.	$\bar{X}$	517	10 063	307	0.012
		CV	15.7	39.6	64.4	41.7
6	*Alnus acuminata* Kunth	$\bar{X}$	528	10 072	897	0.019
		CV	3.9	11.3	20.8	68.4
7	*Swietenia macrophylla* King	$\bar{X}$	531	10 340	624	0.015
		CV	6.5	25.5	60.4	66.7
8	*Fraxinus uhdei* (Wenz.) Lingelsh	$\bar{X}$	592	9 693	1 206	0.010
		CV	2.9	7.9	10.9	70.0
9	*Tabebuia donnell-smithii* Rose	$\bar{X}$	598	9 726	1 084	0.025
		CV	3.6	29.1	43.9	52.0
10	*Dalbergia paloescrito* Rzedowski & Guridi Gómez	$\bar{X}$	624	10 493	1 126	0.023
		CV	7.7	27.4	20.0	34.8
11	*Tabebuia rosea* (Bertol.) Bertero ex A.DC.	$\bar{X}$	635	10 425	1 032	0.042
		CV	5.4	15.1	15.5	57.1
12	*Fagus mexicana* Martínez	$\bar{X}$	642	12 428	747	0.019
		CV	7.5	36.0	44.4	73.7
13	*Andira inermis* (W.Wright) DC.	$\bar{X}$	716	10 071	1 084	0.013
		CV	4.0	12.5	38.2	76.9
14	*Psidium sartorianum* (O.Berg) Nied.	$\bar{X}$	789	11 261	1 067	0.025
		CV	3.6	28.4	61.4	52.0
15	*Juglans pyriformis* Liebm.	$\bar{X}$	810	14 441	1 369	0.018
		CV	3.3	27.1	54.4	50.0
16	*Caesalpinia platyloba* S.Watson	$\bar{X}$	825	15 093	1 511	0.023
		CV	2.6	17.1	24.7	60.9
17	*Albizzia plurijuga* (Standl.) Britton & Rose	$\bar{X}$	844	15 796	1 792	0.023
		CV	6.7	7.3	16.0	43.5
18	*Quercus* spp.	$\bar{X}$	847	18 150	1 318	0.040
		CV	3.5	17.1	22.0	75.0
19	*Lysiloma acapulcensis* (Kunth) Benth.	$\bar{X}$	974	15 630	2 114	0.031
		CV	3.7	7.1	13.6	32.3
20	*Cordia elaeagnoides* A. DC in DC.	$\bar{X}$	992	18 588	1 449	0.017
		CV	8.2	23.0	46.4	58.8
21	*Acosmium panamense* (Benth.) Yakovlev	$\bar{X}$	1 005	18 644	1 622	0.013
		CV	6.2	14.6	50.3	76.9
22	*Tabebuia chrysantha* (Jacq.) & G.Nicholson	$\bar{X}$	1 096	18 623	2 320	0.029
		CV	2.2	9.6	12.2	34.5

ρ = Density; E_{vt} = Dynamic module; G_{vt} = Rigidity module; ζ_{vt} = Damping coefficient; $\bar{X}$ = Mean; CV = Variation coefficient in percentage.

From five pieces of wood of each species, 20 specimens of 0.05 m × 0.05 m in their cross section and 0.4 m - 0.5 m long, containing only sapwood and free of knots and deviations from the fiber were prepared. The specimens were oriented in the radial, tangential and longitudinal directions of the wood plane (Figure 1). Wood was stabilized for 24 months in a 2006 FITECMA conditioning chamber at 20 °C (± 1 °C) and a relative humidity of 60 % (± 2 %), until it reached a constant weight. The moisture content of the wood was determined by the weight difference method with complementary groups of standardized test pieces with dimensions of 0.02 m × 0.02 m × 0.06 m (ISO, 2014a). Using these complementary groups of test pieces, the density of the wood was calculated with the weight / volume ratio at the time of the test (ISO, 2014b). To estimate weight, an Ohaus Scout Pro SP2001 electronic balance, with a 200 g capacity and an accuracy of 0.01 g was used; while to measure volume, a Truper® CALDU-6mp caliper, with capacity of 150 mm and with a 0.01 mm accuracy, was used.



Source: Sotomayor-Castellanos *et al*. (2015).

Nodo = Node; *Primer modo de vibración* = First vibration mode; *Probeta* = Specimen; *Acelerómetro* = Accelerometer; P = Impact; L = Longitudinal direction and/or specimen's length; R = Radial direction; T = Tangential direction.

Figure 1. Configuration of the vibration tests

Methods

The vibration tests followed the protocol proposed by Sotomayor-Castellanos *et al*. (2015) and consisted of moving the specimen in free-support condition and measuring the two natural frequencies corresponding to the first and second vibration modes. At the same time, the signal of the temporary decrement of the vibrations was captured. The free-free condition was accomplished by holding the specimen to two elastic supports considered with negligible rigidity and both placed in the nodes of the first vibration mode of the specimen. The configuration of the tests is shown in Figure 1.

The vibrations were achieved by means of an elastic impact (P) in the direction transverse to the longitudinal direction (L) of the specimen by a Piezotronics™ PCB hammer, 086B05 SN 4160 model. To measure the displacement of the specimen in the transverse direction, a Piezotronics™ PCB accelerometer, 353B04 model (weight = 10.5 g) was placed on one end of each piece of wood, adhered with an adhesive wax (Petro Wax 080A109, PCB Piezotronics™.

Once the specimen was in vibration, the first two natural frequencies were measured from the frequency domain diagram obtained with an algorithm of the fast Fourier transform. At the same time, the logarithmic decrement was calculated from the damping signal of the vibrations. The natural frequencies and the logarithmic decrement were calculated by a Brüel and Kjær® dynamic signal analyzer, 986A0186 model, provided with a Brüel and Kjær® data acquisition and processing program, DSA-104 model. The intensity of the impact and the amplitude of the vibrations were regulated with the help of the data acquisition and processing system.

The dynamic test in each test piece was repeated three times and the average of measured values was considered for further analysis. During the test, the moment of inertia of the cross section of the test specimen corresponding to the test was determined with the formula:

$$I = \frac{b\,h^3}{12}$$

(Equation 1)

Where:

I = Moment of inertia of the cross section (m^4)

b = Base of the test piece (m)

h = Height of the specimen

All the calculated parameters are marked with the subscript "vt" to identify them as derivatives of cross-sectional vibration tests.

The model used to determine the modulus of elasticity and rigidity, was the equation of movement of a beam in transverse vibrations (1) proposed by Weaver *et al.* (1990)

$$E\,I\,\frac{\partial^4 y}{\partial x^4} + m\,\frac{\partial^2 y}{\partial t^2} - \left(m\,r^2 + \frac{E\,I\,m}{K'\,A\,G}\,\frac{\partial^4 y}{\partial x^2\,\partial t^2}\right) + \frac{m^2\,r^2}{K'\,A\,G}\,\frac{\partial^4 y}{\partial t^4}$$

(Equation 2)

Where:

E = Dynamic module (N m^{-2})

G = Rigidity module (N m^{-2})

I = Moment of inertia of the cross section (m^4)

m = Mass per unit length (kg m^{-1})

r = Turning radius of the cross section (m^2)

A = Area of the cross section (m^2)

K' = Shape factor in shear

To solve equation (1), the numerical solution developed for its application in wooden specimens by Brancheriau and Baillères (2002) was used.

The damping coefficient was calculated from the damping signal of the vibrations with the equation (2) used by Labonnote *et al.* (2013):

$$\zeta_{vt} = \frac{\delta}{2}$$

(Equation 3)

Where:

ζ_{vt} = Damping coefficient

δ = Logarithmic decrease

$$\text{With: } \delta = \ln \frac{A_n}{A_{n+1}} \quad \text{(Equation 4)}$$

Where:

A_n = Amplitude of the vibration in the *n* cycle (*m*)

A_{n+1} = Amplitude of vibration in *n* cycle + 1 (*m*)

Experimental design. In order to verify the normality of the distributions of the variables of response density, dynamic modulus, modulus of rigidity and coefficient of damping, the pointing and bias of the corresponding samples were calculated. When the normality test verified that the data came from normal distributions, an experiment was designed following the recommendations of Gutiérrez and De la Vara (2012).

For each variable, its mean, standard deviation and percentage coefficient of variation were calculated. The species was considered the variation factor. The regressions and their coefficients of determination were calculated for a level of significance of 95 %, of the modulus of elasticity, of stiffness and of the damping coefficients as a function of density. The results were compared with those reported in the literature.

Results and Discussion

Table 1 shows the density and dynamic characteristics of the 22 woods. The species are arranged in ascending order with respect to their density. The moisture content of the wood was on average 11.5 % with a coefficient of variation of 1 %. It was considered that the moisture content was uniform in all wood samples and that it did not intervene significantly in the results.

The magnitude of the first frequency f1 varied from 756 Hz to 1 264 Hz, with a coefficient of variation of 16 %. The magnitude of the second frequency f2 varied from 1 877 Hz to 2 858 Hz, with a coefficient of variation of 20 %. The specific values to each test piece were used in the solution of Equation (1).

For the 22 woods, the values of bias and pointing included within the interval -2, +2, verified that the data of the density and of the dynamic and rigidity modules came from normal distributions. Particular case was the bias of the damping coefficient that showed a value of 2.46, that is, it was outside the expected range for data from a normal distribution. Likewise, for the damping coefficient, the aiming was -0.1863 and it was within the expected range for data from a normal distribution.

Density

The dynamic properties of wood depend, among other factors, on its porosity and the arrangement of its anatomical elements that serve as structures of mechanical resistance (Spycher *et al*., 2008; Salmén and Burgert, 2009; McLean *et al.,* 2012). In the same context, the basic chemical composition of wood and its extractable substances influence the variability of dynamic properties between species, within a species and in the position and type of wood in a tree (Thibaut *et al.,* 2001; Carlquist, 2012, Se Golpayegani *et al.,* 2012; Brémaud *et al.,* 2013). However, wood density is the physical parameter that is considered most useful as a predictor of mechanical characteristics (Niklas and Spatz, 2010).

The magnitude of the density of the wood was distributed between a minimum of 391 kg m^{-3} (*Gyrocarpus americanus* Jacq.) and a maximum of 1 096 kg m^{-3} [*Tabebuia* *chrysantha*(Jacq.) & G.Nicholson], which allowed to examine a wide range of densities. With the exception of the wood of *Cedrela odorata* L., the coefficient of variation of the density of each species was below 10 %, a value similar to that registered by the Forest Products Laboratory of the United States of America (Forest Products Laboratory, 2010). This result confirms the variability of the density of each species. The density acted as a good predictor of the dynamic module (Figure 2) and the rigidity module (Figure 3). On the other hand, a significant correlation of the damping coefficient with density was not verified (Figure 4).

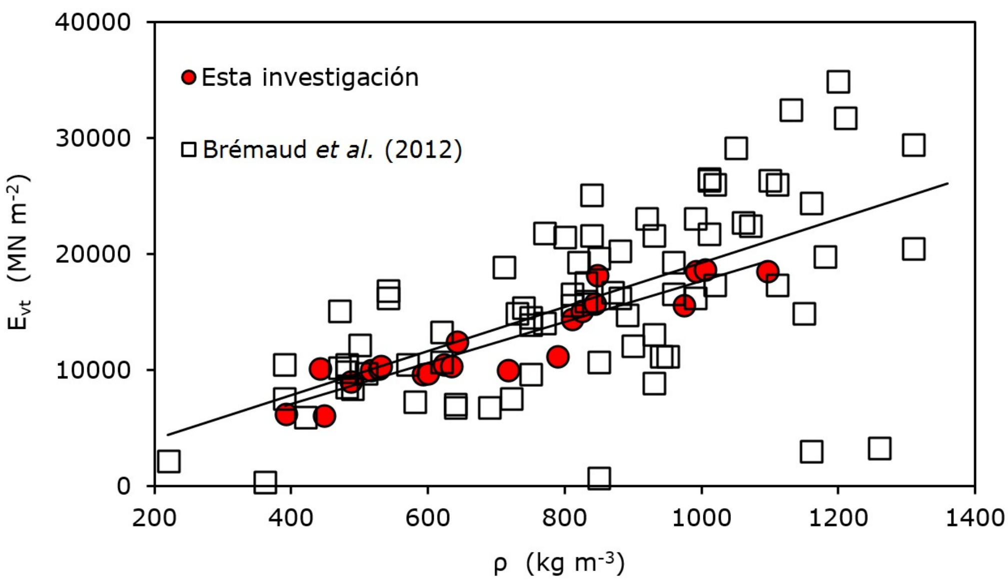


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Figure 2. Dynamic modulus as a function of density.

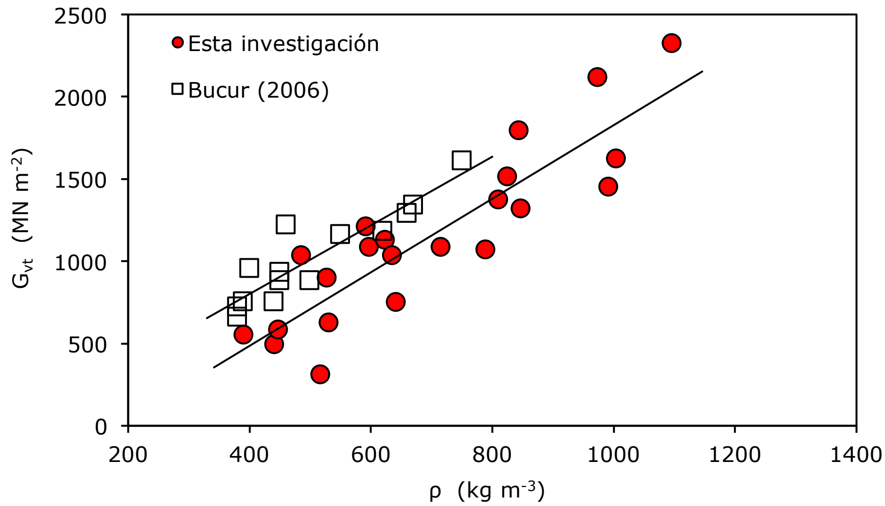

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Figure 3. Rigidity modulus as a function of density.

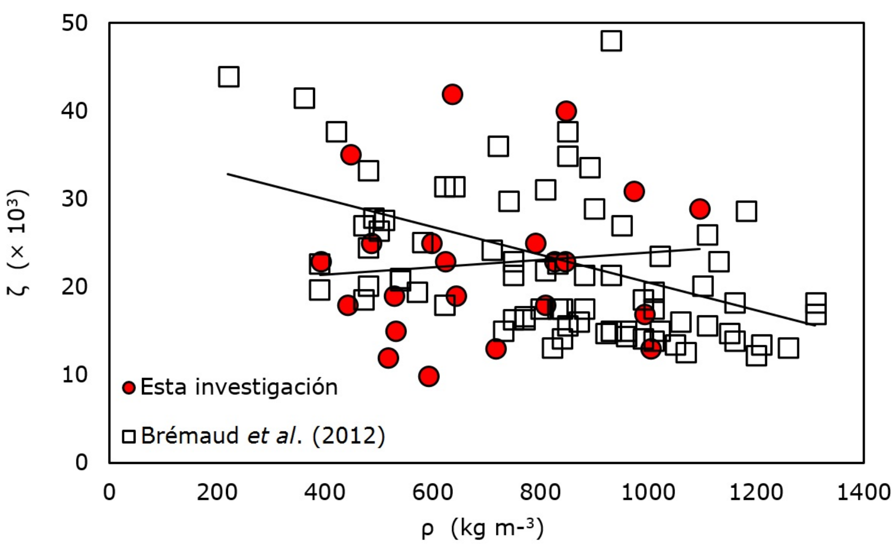

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Figure 4. Damping coefficient as a function of density.

Dynamic modulus

The magnitude of the dynamic module was between a minimum value of 6 076 MN m^{-2} [*Enterolobium cyclocarpum* (Jacq.) Griseb] and a maximum of 18 644 MN m^{-2} [*Acosmium panamense* (Benth.) Yakovlev] (Table 1). The dispersion of the dynamic module as a function of the density of the 22 woods of this investigation (Figure 2, Table 2) is compared to data of the dynamic module determined by transverse vibrations of Brémaud *et al.* (2012).

Table 2. Regressions and coefficients of determination.

This research	R^2	Brémaud *et al*. (2012)	R^2
E_{vt} = 17.608 ρ + 50.7	0.86	E_{vt} = 23.238 ρ - 2410.6	0.60
This research		Bucur (2006)	
G_{vt} = 2.235 ρ - 406.5	0.79	G_{vt} = 2.092 ρ - 37.6	0.83
This research		Brémaud *et al*. (2012)	
ζ_{vt} = 0.004 ρ + 19.7	0.01	ζ_{vt} = -0.016 ρ + 36.4	0.16

ρ = Density; *Evt* = Dynamic module; *Gvt* = Stiffness module; *ζvt* = Damping coefficient; R^2 = Coefficient of determination

These results describe the diversity in the mechanical characteristics found in the woods studied and coincide with the deductions of Bao *et al.* (2001) and Baillères *et al.* (2005). The variability of the technological properties of wood originates mainly from the diversity of the environment where the trees grow and the morphogenetic properties of the species.

The coefficient of variation of the dynamic modulus ranged between 7.1 % [*Lysiloma acapulcensis* (Kunth) Benth.] and 39.9 % (*E. cyclocarpum*). This variability within the species is of the same magnitude as that found by several researchers: Cho (2007) reports for five species a coefficient of variation ranging from 17.3 % to 25.2 %, species with densities of 419 kg m^{-3} a 612 kg m^{-3}; Hamdam *et al.* (2009) found coefficients of variation for six tropical species for the dynamic modulus of tropical woods ranging from 9.1 % to 30 % (240 kg m^{-3} <ρ <440 kg m^{-3}). Brémaud *et al.* (2012) determined for 98 species with a range of densities between 210 kg m^{-3} and 1 380 kg m^{-3}, coefficients of variation that reach 33 %; Da Silva *et al.* (2012) published a coefficient of variation of 19.6 % for *Copaifera langsdorffii* Desf. wood (ρ = 844 kg m^{-3}). This variation in the results can be explained from two perspectives.

On the one hand, the specimens were selected making sure that they did not have growth defects such as knots and fiber deviation. However, in the case of the woods studied and classified as tropical from temperate and humid climates (Tamarit and López, 2007; Silva *et al.,* 2010), it is difficult to find pieces of wood without growth anomalies. On the other hand, the pieces of wood from which the specimens were prepared, were acquired in establishments where wood from different geographical origins is gathered, which probably introduced a variability due to the quality of the station where the trees grew and this can be added to the natural variation within a species (Forest Products Laboratory, 2010). However, this result allowed observing the wide range of values of the dynamic module that can be found between different species.

Rigidity modulus

The rigidity modulus of wood varied from a minimum of 307 MN m^{-2} (*C. odorata*) to 2 320 MN m^{-2} (*T. chrysantha*) (Table 1). Comparatively, Yoshihara and Kubojima (2002) recorded a rigidity modulus of 1 250 KN m^{-2} for *Pinus densiflora* Siebold. & Zucc. wood (ρ = 660 kg m^{-3}) and for *Fraxinus spaethiana* Lingelsh. Gvt = 910 MN m^{-2} (ρ = 580 kg m^{-3}); Cho (2007) refers rigidity modules from 650 MN m^{-2} to 1 070 MN m^{-2} for five wood species (419 kg m^{-3} <ρ <612 kg m^{-3}); Hassan *et al.* (2013) report a Gvt of 570 MN m^{-2} for *Pinus sylvestris* L. wood with a density of 453 kg m^{-3}; for the same species, Roohnia and Kohantorabi (2015) refer rigidity modules that vary from 594 KN m^{-2} to 941 KN m^{-2} (342 kg m^{-3} <ρ <420 kg m^{-3}).

The magnitude of the rigidity modulus of the 22 woods studied is similar to that described by Bucur (2006), which exhibits a higher coefficient of determination compared to that of this investigation (Figure 5). The density of the wood is a predictor of the rigidity modulus (Table 2). Its coefficient of determination suggests that it is possible to estimate the rigidity module with certainty, which facilitates obtaining numerical values of this parameter that is complicated to determine experimentally.

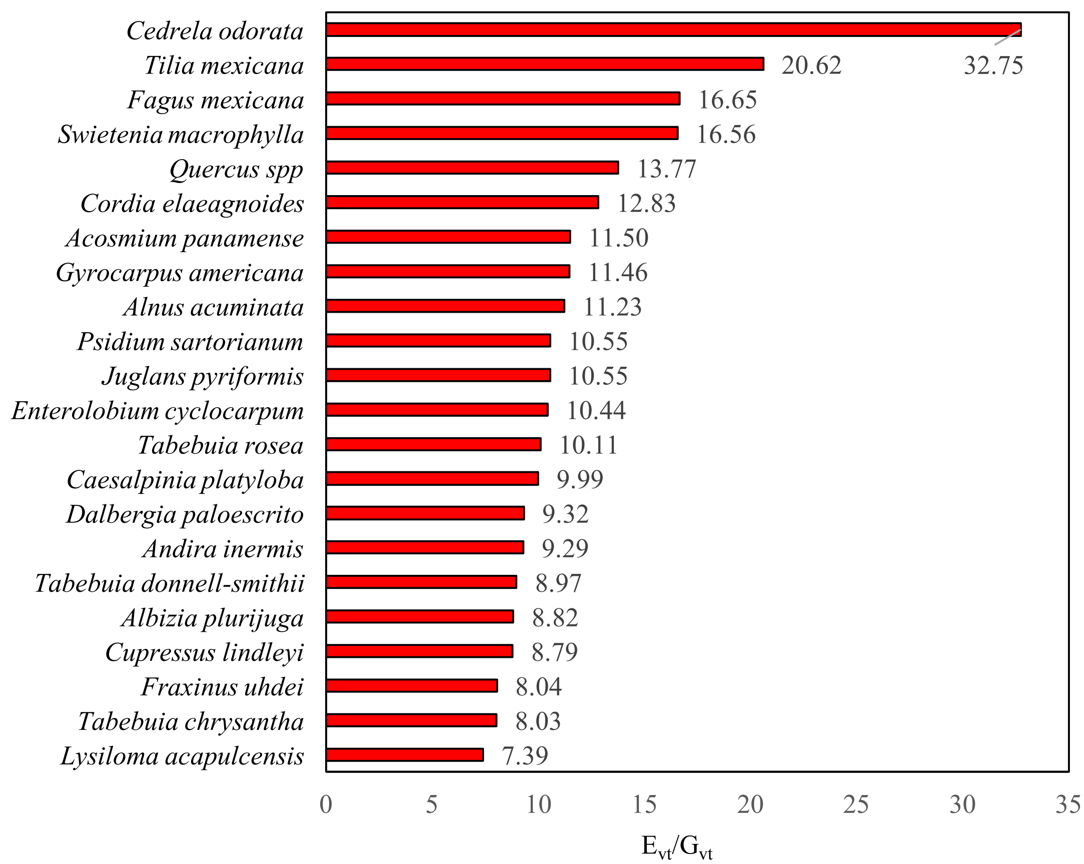

Figure 5. Ratio between the elasticity modulus and the rigidity modulus (Evt / Gvt).

The rigidity modulus exhibited coefficients of variation ranging from a minimum of 10.9 % (*F. uhdei*) to a maximum of 64.4 % (*C. odorata*) (Table 1). Several authors have also observed such variation. Cho (2007) established a coefficient of variation between 13.6 % and 24.6 % for five species; Da Silva *et al.* (2012) deterrmined a coefficient of variation for the rigidity modulus of 43.3 % for *Copaifera langsdorffii* Desf. wood (ρ = 844 kg m^{-3}); the coefficient of variation of Hassan *et al.* (2013) was 21.3 % for *Pinus sylvestris* (ρ = 453 kg m^{-3}); moreover, Roohnia and Kohantorabi (2015) obtained variation in the rigidity modules caused by the differences in the modality of the test used in their determination and this variability in the results between species goes along with the natural variation within a species.

Damping coefficient

The damping coefficient varied between a minimum of 0.010 (*F. uhdei*) and a maximum of 0.042 [*Tabebuia rosea* (Bertol.) Bertero ex A.DC.] (Table 1), values similar to those recorded by Brémaud *et al.* (2012) (Figure 4).

The coefficients of variation of the damping coefficient were between 32.3 % and 76.9 % and are higher than those found by other authors. The coefficients of variation of Sedik *et al.* (2010) range from 9.5 % to 29.4 % (210 kg m^{-3} $<ρ<$350 kg m^{-3}). Values of the coefficient of variation between 16 % and 44 % correspond to Da Silva *et al.* (2012) for *Copaifera langsdorffii* wood (ρ = 844 kg m^{-3}). Brémaud *et al.* (2011) and Brémaud *et al.* (2012) reported coefficients of variation up to 41 % (210 kg m^{-3} $<ρ<$1 380 kg m^{-3}).

Figure 4 represents the dispersions of the damping coefficient as a function of the density of 22 woods of this research and is contrasted with the data of Brémaud *et al.* (2012). The linear regression between ζvt and ρ is very weak (Table 2) and the results are mixed with those of that author; this number is similar to those of the same author (2011) and those of Brancheriau *et al.* (2010). From the analysis of the results of this investigation and based on those of the cited authors, it can be deduced that, for the woods studied, the damping coefficient in transverse vibrations is independent of density.

Characteristics variability

The variation found in the values of the dynamic characteristics of the 22 species is similar to that of wood in general (Tamarit and López, 2007; Silva *et al*., 2010; Sotomayor, 2015). This result can be explained from several perspectives.

The first of them, due to the wide material heterogeneity in different observation scales (Hofstetter *et al.,* 2005) and the diversity in the types and arrangement of their anatomical structure of wood (Guitard and Gachet, 2004). In addition, wood is an anisotropic material, that is, the magnitude of its characteristics differs according to the direction of observation (Brémaud *et al*., 2011).

Indeed, in the wood of angiosperm species, it is common to find crisscrossed thread, corrugated fiber and spiral, which possibly increased the variability of the results (Harris, 1989). Also, taking into account the considerations of Obataya *et al.* (2000) and Brancheriau *et al.* (2006), the porosity proper to each species, as well as the different percentages of rays in the woody plane of each of the woods studied, possibly influenced the magnitudes of the determined dynamic characteristics.

A second explanation of the variation refers to the parameters that describe the dynamic behavior of the wood, are related to the configuration of the tests carried out, particularly with the excitation frequencies (Chui and Smith, 1990). In this way, the results reported here refer to a range of the first resonance frequency between 756 Hz and 1 234 Hz and the second one of 1 877 Hz and 2 858 Hz. Although these magnitudes are similar to those reported by Brancheriau *et al.* (2010) for dynamic bending tests with specimens of similar dimensions to those made here, each test represents a particular movement system and, consequently, the measurements may vary.

These particularities in the material structure of the wood and its mechanical behavior are reflected in an important difference between its modulus of elasticity and its rigidity modulus. To illustrate this particularity, Figure 5 presents the ratio between the modulus of elasticity and the rigidity modulus Evt / Gvt for the 22 woods, which varies between 7.39 (*L. acapulcensis*) and 32.75 (*C. odorata*). These relationships are similar to those reported by Brémaud *et al.* (2011) (5.3 <Evt / Gvt <26.5) and Cha (2015) (9.6 <Evt / Gvt <21.3), with the exception of *C. odorata*, which has an extreme and exceptional value. This perspective allows relatively positioning each species with respect to the set of woods studied. The Evt / Gvt ratio distinguishes the shape of the vibration mode of a piece of wood and the magnitude of its frequency Brémaud *et al.* (2011). The higher the Evt / Gvt ratio, the lower the frequency.

As a prospective, the dynamic characteristics of the 22 woods studied may be useful for the valuation of these species in structural uses, particularly if they are used as non-destructive methods to estimate the resistance of wood for structural purposes. This classification must be established from parameters that are measurable in wood and independent of the species, as are the dynamic characteristics determined here (Ravenshorst *et al*., 2013).

Conclusions

By means of vibration tests, density, dynamic modulus, rigidity modulus and damping coefficient of 22 woody species were determined. Each species presents different magnitudes of its dynamic characteristics. Their coefficients of variation are diverse and they are located within the scale for tropical woods reported in literature. The knowledge of the dynamic characteristics allows to differentiate each species for a possible particular use. If they are compared with the results reported in the bibliography, wood is probably valued for use in functions where mechanical resistance is important. The regression models for the dynamic and rigidity module as a function of density favorably explain the variability of the sample studied, so that the density was a good predictor of the dynamic module and the rigidity module. In contrast, no significant correlation of the damping coefficient with density was found.

Conflict of interests

The author declares no conflict of interests.

Contribution by author

The author is responsible for the research that supports this contribution and the manuscript in its entirety.

References

Baillères, H., O. Vitrac and T. Ramananantoandro. 2005. Assessment of continuous distribution of wood properties from a low number of samples: application to the variability of modulus of elasticity between trees and within a tree. Holzforschung 59(5):524-530.

Bao, F. C., Z. H. Jiang, X. M. Jiang, X. X. Lu, X.Q. Luo and S. Y. Zhang. 2001. Differences in wood properties between juvenile wood and mature wood in 10 species grown in China. Wood Science and Technology 35(4):363-375.

Brancheriau, L. and H. Baillères. 2002. Natural vibration analysis of clear wooden beams: a theoretical review. Wood Science and Technology 36(4):347-365.

Brancheriau, L., H. Baillères, P. Détienne, J. Gril and R. Kronland. 2006. Key signal and wood anatomy parameters related to the acoustic quality of wood for xylophone-type percussion instruments. Journal of Wood Science 52(3):270-273.

Brancheriau L., C. Kouchade and I. Brémaud. 2010. Internal friction measurement of tropical species by various acoustic methods. Journal of Wood Science 56(5):371-379.

Brémaud, I., K. Minato, P. Langbour and B. Thibaut. 2010. Physico-chemical indicators of inter-specific variability in vibration damping of wood. Annals of Forest Science 67(7):707-714.

Brémaud, I., J. Gril and B. Thibaut. 2011. Anisotropy of wood vibrational properties: dependence on grain angle and review of literature data. Wood Science and Technology 45(4):735-754.

Brémaud, I. 2012. Acoustical properties of wood in string instruments soundboards and tuned idiophones: Biological and cultural diversity. Journal of the Acoustical Society of America 131(1):807-818.

Brémaud, I., Y. El Kaïm, D. Guibal, K. Minato, T. Thibaut and J. Gril. 2012. Characterization and categorization of the diversity in viscoelastic vibrational properties between 98 wood types. Annals of Forest Science 69(3): 373-386.

Brémaud, I., J. Ruelle, A. Thibaut and B. Thibaut. 2013. Changes in viscoelastic vibrational properties between compression and normal wood: roles of microfibril angle and of lignin. Holzforschung 67(1):75-85.

Bucur, V. 2006. Acoustics of Wood. 2nd edition. Springer. Heidelberg, Germany. 394 p.

Carlquist, S. 2012. How wood evolves a new synthesis. Botany 90(10):901-940.

Cha, J. K. 2015. Determination of true modulus of elasticity and modulus of rigidity for domestic woods with different slenderness ratios using nondestructive tests. Journal of the Korean Wood Science and Technology 43(1):36-42.

Cho, C. L. 2007. Comparison of Three Methods for Determining Young's Modulus of Wood. Taiwan Journal of Forest Science 22(3):297-306.

Chui, Y. H. and I. Smith. 1990. Influence of rotatory inertia, shear deformation and support condition on natural frequencies of wooden beams. Wood Science and Technology 24(3):233-245.

Da Silva L., E. R., P. R. Gherardi H., T. Moreira D. and G. F. Rabelo. 2012. Estimation of the dynamic elastic properties of wood from *Copaifera langsdorfffi* Desf using resonance analysis. CERNE 18(1):41-47.

Forest Products Laboratory .2010. Wood handbook. Wood as an Engineering Material. Forest Products Laboratory. Madison, WI, USA. 508 p.

Guitard, D. and C. Gachet. 2004. Paramètres structuraux et/ou ultrastructuraux facteurs de la variabilité intra-arbre de l'anisotropie élastique du bois. Annals of Forest Science 61(2):129-139.

Gutiérrez P., H. y R. De la Vara S. 2012. Análisis y diseño de experimentos. Mc Graw Hill. México, D.F., México. 590 p.

Hamdam, S., Y. Sedik, I. Jusoh, M. Hasan and Z. A. Talib. 2009. Dynamic Young´s modulus and glass transition temperature of selected tropical wood species. Materials Science and Technology 25(6):805-808.

Harris, J. M. 1989. Spiral grain and wave phenomena in wood formation. Springer. Berlin, Germany. 215 p.

Hassan, K. T. S., P. Horáček and J. Tippner. 2013. Dynamic tests of wood. BioResources 8(2):1634-1645.

Hofstetter, K., C. Hellmich and J. Eberhardsteiner. 2005. Development and experimental validation of a continuum micromechanics model for the elasticity of wood. European Journal of Mechanics A/Solids 24(6):1030-1053.

International Organization for Standardization (ISO). 2014a. ISO 13061-1:2014 Wood. Determination of moisture content for physical and mechanical tests. International Organization for Standardization. Geneva, Switzerland. 4 p.

International Organization for Standardization (ISO). 2014b. ISO 13061-2:2014 Wood. Determination of density for physical and mechanical tests. International Organization for Standardization. Geneva, Switzerland. 5 p.

Jae-Woo, K., D. P. Harper and A. M. Taylor. 2009. Effect of wood species on the mechanical and thermal properties of wood-plastic composites. Journal of Applied Polymer Science 112(3):1378-1385.

Köhler, J., J. D. Sørensen and M. H. Faber. 2007. Probabilistic modeling of timber structures. Structural Safety 29(4):255-267.

Labonnote, N., A. Rønnquist and K. A. Malo. 2013. Experimental evaluations of material damping in timber beams of structural dimensions. Wood Science and Technology 47(5):1033-1050.

Labonnote, N., A. Rønnquist and K. A. Malo. 2015. Prediction of material damping in timber floors, and subsequent evaluation of structural damping. Materials and Structures 48(6):1965-1975.

McLean, J. P., O. Arnould, J. Beauchêne and B. Clair. 2012. The effect of the G-layer on the viscoelastic properties of tropical hardwoods. Annals of Forest Science 69(3):399-408.

Niklas, K. J. and H. C. Spatz. 2010. Worldwide correlations of mechanical properties and green wood density. American Journal of Botany 97(10):1587-1594.

Obataya, E., T. Ono and M. Norimoto. 2000. Vibrational properties of wood along the grain. Journal of Materials Science 35(12):2993-3001.

Olsson, A., J. Oscarsson, M. Johansson and B. Källsner. 2012. Prediction of timber bending strength on basis of bending stiffness and material homogeneity assessed from dynamic excitation. Wood Science and Technology 46(4):667-683.

Ouis, D. 2003. Effect of structural defects on the strength and damping properties of a solid material. European Journal of Mechanics A/Solids 22(1):47-54.

Pellerin, R. F. and R. J. Ross. 2002. Nondestructive Evaluation of Wood. Forest Products Society. Peachtree Corners, GA, USA. 210 p.

Piter, J. C., R. L. Zerbino and H. J. Blaß. 2004. Effectiveness of fundamental resonant frequency for determining the elastic properties of Argentinean *Eucalyptus grandis* in structural sizes. Holz Roh Werkst 62(2) 88-92.

Ravenshorst, G. J. P., W. F. Gard and J. W. G. Van De Kuilen. 2013. The importance of characterisation and sampling of tropical wood species with regard to strength and durability classification. Heron 53(2-3):201- 228.

Roohnia, M. and M. Kohantorabi. 2015. Dynamic methods to evaluate the shear modulus of wood. BioResources 10(3):4867-4876.

Ross, R. J. (Ed.). 2015. Nondestructive evaluation of wood: second edition. General Technical Report FPL-GTR-238. Forest Products Laboratory. Madison, WI, USA. 169 p.

Salmén, L. and I. Burgert. 2009. Cell wall features with regard to mechanical performance. A review. Holzforschung 63(2):121-129.

Se Golpayegani, A., I. Brémaud, J., Gril, M-F. Thevenon, O. Arnould and K. Pourtahmasi. 2012. Effect of extractions on dynamic mechanical properties of white mulberry (*Morus alba*). Journal of Wood Science 58(2):153-162.

Sedik, Y., S. Hamdan, I. Jusoh and M. Hasan. 2010. Acoustic Properties of Selected Tropical Wood Species. Journal of Nondestructive Evaluation 29(1):38-42.

Silva G., J. A., T., F. J. Fuentes, R. Rodríguez A., P. A. Torres A., M. A. Lomelí R., J. Ramos Q., C. Waitkus and H. G. Richter. 2010. Fichas de propiedades tecnológicas y usos de maderas nativas de México e importadas. Comisión Nacional Forestal. Zapopan, Jal., México. 186 p.

Sotomayor C., J. R. 2015. Banco FITECMA de características físico-mecánicas de maderas mexicanas. Universidad Michoacana de San Nicolás de Hidalgo. Morelia, Mich., México. 65 p.

Sotomayor-Castellanos, J. R., G. Suárez-Béjar y J. B. Olguín-Cerón. 2015. Efecto del tratamiento higro-térmico en las características acústicas de la madera de *Quercus scytophylla*. Madera y Bosques 21(1): 139-156.

Spycher, M., F. W. R. Schwarze and R. Steiger. 2008. Assessment of resonance wood quality by comparing its physical and histological properties. Wood Science and Technology 42(4):431-440.

Sucharda, O., D. Mikolasek and J. Brozovsky. 2015. Finite element analysis and modeling of details timber structure. International Journal of Mathematical Models and Methods in Applied Sciences 9:380-388.

Tamarit U., J. C. y J. L. López T. 2007. Xilotecnología de los principales árboles tropicales de México. CIRGOC Instituto Nacional de Investigaciones Forestales, Agropecuarias y Pecuarias. Libro Técnico Núm. 7. San Martinito Tlahuapan, Pue., México. 264 p.

Thibaut, B., J. Gril and M. Fournier. 2001. Mechanics of wood and trees: some new highlights for an old story. Comptes Rendus de l'Académie des Sciences. Séries IIB Mechanics 329(9):701-716.

Wang, Z., L. Li and M. Gong. 2012. Measurement of dynamic modulus of elasticity and damping ratio of wood-based composites using the cantilever beam vibration technique. Construction and Building Materials 28(1):831-834.

Weaver, W. Jr., S. Timoshenko and D. H. Young. 1990. Vibration problems in engineering. Wiley. New York, NY, USA. 624 p.

Yoshihara, H. and Y. Kubojima. 2002. Measurement of the shear modulus of wood by asymmetric four-point bending tests. Journal of Wood Science 48(1):14-19.